



Heteropoly acid catalysts in upgrading of biorenewables: Cycloaddition of aldehydes to monoterpenes in green solvents

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ABSTRACT

Acidic Cs salt of tungstophosphoric heteropoly acid, $\text{Cs}_{2.5}\text{H}_{0.5}\text{PW}_{12}\text{O}_{40}$ (CsPW), is excellent solid acid catalyst for liquid-phase cycloaddition reactions of biomass-based and easily available from essential oils monoterpene compounds, such as limonene, α -terpineol, α -pinene, β -pinene and nerol, with aldehydes, including benzaldehyde, crotonaldehyde as well as biomass-derived cuminaldehyde and *trans*-cinnamaldehyde. The reactions give oxabicyclo[3.3.1]nonene compounds potentially useful for the fragrance and pharmaceutical industries in good to excellent yields. The process is environmentally benign and can be performed in biomass-derived solvent 2-methyltetrahydrofuran and eco-friendly “green” organic solvents such as dimethylcarbonate and diethylcarbonate under mild conditions at low catalyst loadings without leaching problems. The solid CsPW catalyst can be easily separated from the reaction media and low-boiling solvents can be removed by distillation. Silica-supported $\text{H}_3\text{PW}_{12}\text{O}_{40}$ also demonstrated good performance in these reactions.

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1. Introduction

Mitigating the environmental impact of industrial chemical processes is one of the main topics in modern chemistry, in particular, catalytic chemistry. Although the use of catalytic rather than stoichiometric reactions is already among the requirements of green organic synthesis, the development of environmentally benign catalytic processes remains a challenge. In this connection, the use of renewable reagents and non-toxic biodegradable solvents (or no solvent at all) as well as heterogeneous catalysis, which allows facile catalyst separation and reduction of waste, is particularly important for the design of sustainable eco-friendly catalytic processes.

Numerous terpene compounds found in essential oils (often as main constituents) are widely used in the fragrance, pharmaceutical and cosmetic industries [1–3]. Besides, terpenes can be chemically transformed into value-added products and therefore represent an abundant feedstock of renewable biomass-based substrates for chemical industry [1–8]. A variety of chemical reactions has been used for the catalytic upgrading of terpenes, such as hydroformylation, oxidation, epoxidation and hydrogenation

[4–8]. Acid-catalyzed transformations can also lead to various useful commercial chemicals starting from terpenes [6,9,10]. Most of these processes still use large amounts of mineral acids as catalysts and operate under homogeneous conditions with serious corrosion and waste problems.

Heteropoly acids (HPAs) due to their unique properties represent an attractive and environmentally friendly alternative to conventional acid catalysts such as mineral acids, ion-exchange resins, zeolites and clays [11–13]. First few examples of the application of heteropoly compounds (HPCs) for the transformations of terpenes were published in the 1990s [14–16]. Over the last decade, the interest to this promising topic has greatly increased [13]. HPAs usually show better catalytic activity and selectivity than the conventional acid catalysts and allow for higher turnover numbers to be obtained due to their stronger acidity. The important advantage of using HPAs in catalysis is the possibility to create heterogeneously-catalyzed processes in both non-polar and polar media. In non-polar solvents HPAs are insoluble and can be used directly as bulk and supported catalysts, e.g., HPA/SiO_2 . In polar solvents, such as water, lower alcohols, acetone, etc., HPAs themselves are highly soluble; however, their acidic salts with large monovalent cations such as $\text{Cs}_{2.5}\text{H}_{0.5}\text{PW}_{12}\text{O}_{40}$ (CsPW) are insoluble and can be applied as heterogeneous acid catalysts. CsPW, possessing strong Brønsted acidity, large surface area and high thermal sta-

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bility, has been successfully used as a solid acid catalyst in several liquid-phase organic reactions [17–22].

Previously, we have applied HPCs as catalysts in various liquid-phase catalytic reactions of terpenes such as isomerization [21,23–26], etherification/esterification [27–29] and coupling with aldehydes [30,31]. In most of these reactions, HPCs have been used as heterogeneous catalysts in appropriate solvents; some of these reactions have been run under solvent free conditions [26], which is the most desirable within the green chemistry concept. As terpenes are highly reactive under acidic conditions, the use of solvents is usually required to avoid product and/or substrate oligomerization. Moreover, the reactions can be strongly dependent on the solvent nature, for example, α -pinene oxide isomerization [24] and coupling of terpenes with aldehydes [30,31].

The use of HPCs as catalysts for cycloaddition of aldehydes to terpenes has first been disclosed in our recent reports [30,31]. This chemistry represents a promising approach to the synthesis of oxygen-containing heterocyclic compounds [10,32–36], in particular, fragrance bicyclic ethers with oxabicyclo[3.3.1]nonene units [33,34,37]. The latter have attracted much attention as ligands for estrogen receptors involved in many physiological processes, e.g., cell growth regulation. Among the solvents used in the reactions of terpenes with aldehydes, satisfactory results have so far been obtained only in toxic and rigorously regulated solvents such as dichloromethane and 1,2-dichloroethane [30–35]. For this reason, our recent studies have been aimed at the search for environmentally friendly reaction media to substitute the chlorinated solvents. Another aim is to extend the scope of substrates to biorenewable aldehydes, i.e., to create processes in which both reagents are derived from biomass.

Recently, organic carbonates, in particular diethylcarbonate DEC and dimethylcarbonate (DMC), have attracted significant interest as green reagents and solvents in organic synthesis due to their biodegradability and low toxicity [38–40]. The production of DEC and DMC does not involve harmful reagents and their degradation does not produce toxic waste or emission of volatile organic compounds as their building block is carbon dioxide. DEC and DMC are both aprotic, weakly basic and low polar solvents (dielectric constant, $\epsilon = 2.8$ for DEC and 3.1 for DMC). Also they have relatively low boiling points compared to other organic carbonates, which allows for their easy distillation from reaction media (b.p. = 126 °C for DEC and 90 °C for DMC).

Here, we describe the cycloaddition reactions of monoterpenes with a series of aldehydes in the presence of silica-supported tungstophosphoric acid $\text{H}_3\text{PW}_{12}\text{O}_{40}$ (HPW) and bulk CsPW as heterogeneous catalysts. Along with conventional 1,2-dichloroethane, these reactions were performed in non-toxic biodegradable “green” organic solvents such as diethylcarbonate and dimethylcarbonate, as well as biomass-derived 2-methyltetrahydrofuran (MeTHF). The following monoterpenes and monoterpene alcohols were used as the substrates: limonene (**1**), α -terpineol (**2**), α -pinene (**3**), β -pinene (**4**), linalool (**5**) and nerol (**6**). As the aldehydes, biomass-derived cuminaldehyde (**7**) and *trans*-cinnamaldehyde (**8**), available from essential oils of eucalyptus and cinnamon, respectively, were used along with crotonaldehyde (**9**) and benzaldehyde (**10**).

2. Experimental

2.1. Chemicals

All chemicals used for the preparation of catalysts and catalytic tests as well as reaction substrates were acquired from Aldrich, except Aerosil 300 silica, which was from Degussa.

2.2. Characterization techniques

The catalysts were characterized by ^{31}P MAS NMR (Bruker Avance DSX 400 NMR, room temperature, spinning rate of 4 kHz, 85% H_3PO_4 as the reference), X-ray diffraction (XRD, Rigaku Geigerflex-3034 diffractometer with $\text{CuK}\alpha$ radiation) and nitrogen physisorption (Micromeritics ASAP 2010 instrument). The content of tungsten and phosphorus in the catalysts was determined by inductively coupled plasma atomic emission spectroscopy (ICP) on a Spectro Ciros CCD instrument.

2.3. Catalyst preparation and characterization

Silica-supported $\text{H}_3\text{PW}_{12}\text{O}_{40}$ (HPW/ SiO_2) was prepared by wet impregnation of Aerosil 300 (BET surface area of $300\text{ m}^2\text{ g}^{-1}$) with an aqueous HPW solution and dried at 130 °C/0.2–0.3 Torr for 1.5 h, as described previously [41]. The BET surface area of the prepared catalyst was $200\text{ m}^2\text{ g}^{-1}$, the pore volume $0.53\text{ cm}^3\text{ g}^{-1}$ and the average pore diameter 144 Å. The ^{31}P MAS NMR spectrum of HPW/ SiO_2 showed only one peak at ca. –15 ppm, characteristic of HPW [42]. As shown by XRD, only a small amount of HPW crystalline phase was present on the catalyst surface, with most of HPW being finely dispersed. The HPW content in the catalyst was 20 wt%.

$\text{Cs}_{2.5}\text{H}_{0.5}\text{PW}_{12}\text{O}_{40}$ (CsPW) was synthesized by dropwise addition of aqueous solution of cesium carbonate (0.47 M) to aqueous solution of HPW (0.75 M) at room temperature with stirring, as described previously [43]. The precipitated CsPW was aged in the aqueous mixture for 48 h at room temperature and dried in a rotary evaporator at 45 °C/3 kPa than in an oven at 150 °C/0.1 kPa for 1.5 h. The BET surface area of the prepared catalyst was $111\text{ m}^2\text{ g}^{-1}$, the pore volume $0.07\text{ cm}^3\text{ g}^{-1}$, and the average pore diameter 24 Å. The acid properties of the prepared catalysts, CsPW and HPW/ SiO_2 , have been studied calorimetrically by ammonia and pyridine adsorption and discussed previously [44,45].

2.4. Catalytic reactions

The catalytic tests were run under air in a 10 mL glass reactor equipped with a reflux condenser to avoid solvent evaporation. In a typical run, a mixture of the substrate (0.45–1 mmol), aldehyde (0.45–1.50 mmol), dodecane (GC internal standard, 0.30 mmol) and the catalyst HPW/ SiO_2 (10–20 mg, 0.70–1.40 μmol of HPW) or CsPW (10–30 mg, 3.0–9.0 μmol), in a specified solvent (3.0 mL) was magnetically stirred at 25–80 °C for a specified time. The reaction mixture was periodically analyzed by gas chromatography (GC, Shimadzu 17 instrument, Carbowax 20 M capillary column, flame ionization detector). Conversions and selectivities presented were obtained by GC and calculated based on the monoterpene substrate (limiting reagent) using dodecane as the internal standard. The difference in mass balance (if any) was attributed to high-boiling products (probably oligomers which could not be detected by GC). In order to control any contribution of homogeneous reactions and catalyst leaching, the catalyst was separated from the reaction mixture by centrifugation (20 °C, 18,000 rpm) and the reaction was allowed to proceed with another portion of monoterpene substrate. The lack of additional substrate conversion indicated the absence of any significant catalyst leaching. In addition, the tungsten content in supernatants was analyzed by atomic absorption spectroscopy (Hitachi-Z8200 spectrometer).

Reaction products were isolated by a column chromatography (silica gel 60) using mixtures of hexane and ethyl acetate as eluents and identified by GC–MS (Shimadzu QP2010-PLUS spectrometer, 70 eV), ^1H , and ^{13}C NMR (Bruker 400 MHz spectrometer, CDCl_3 , TMS).

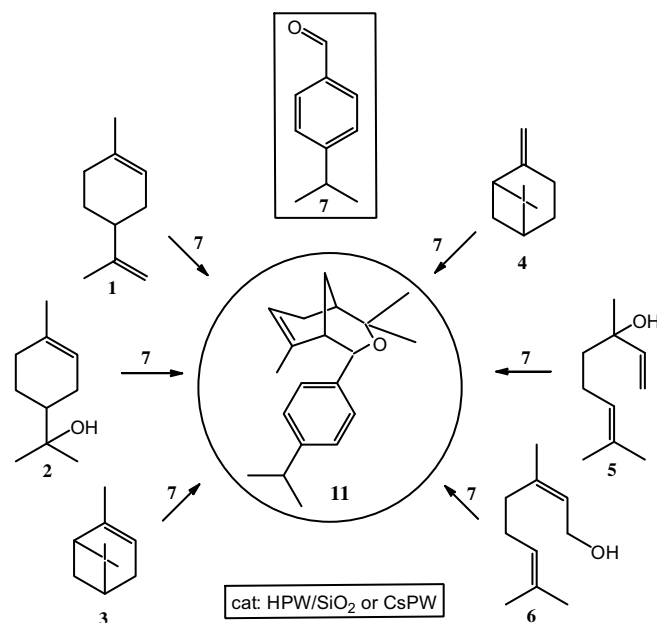
2.5. Spectroscopic data for the products

Compound 11 (new compound): MS (70 eV, EI): m/z 284 (0.2) [M^+], 266 (0.2) [$M^+ - H_2O$], 149 (19), 136 (40%), 121 (10%), 93 (100%), 92 (48%), 91 (18%), 79 (10%), 77 (11%). 1H NMR (400 MHz, $CDCl_3$, 25 °C, TMS), δ = 0.88 (s, 3H; C^7H_3), 1.21 (s, 6H; $C^{19}H_3$ and $C^{20}H_3$), 1.32 (s, 3H; $C^{10}H_3$), 1.37 (s, 3H; C^9H_3), 1.55 (br.s., 1H; C^4H), 1.65–1.75 (m, 1H; C^5HH), 2.00–2.15 (m, 1H; C^3HH), 2.18 (br.s., 1H; C^6H), 2.30–2.45 (m, 2H; C^3HH and C^5HH), 2.86 (br.s., 1H; $C^{18}H$), 4.85 (br.s., 1H; $C^{11}H$), 5.44 (br.s., 1H; C^2H), 7.12 (br.s., 2H; $C^{14}H$ and $C^{16}H$), 7.22 ppm (br.s., 2H; $C^{13}H$ and $C^{17}H$). ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C, TMS), δ = 23.97 (C^7), 24.07 (C^9), 28.70 (C^{10}), 24.18 (C^{19} and C^{20}), 27.73 (C^3), 28.35 (C^5), 33.79 (C^{18}), 33.99 (C^4), 41.49 (C^6), 74.13 (C^{11}), 75.22 (C^8), 123.14 (C^2), 125.57 and 125.81 (C^{13} , C^{14} , C^{16} and C^{17}), 133.39 (C^1), 140.24 (C^{12}), 147.23 ppm (C^{15}). The structure and atom numbering are shown in Schemes 1 and 2.

Compound 12 (new compound), major isomer (shorter GC retention time): MS (70 eV, EI): m/z 268 (0.1) [M^+], 136 (25%), 133 (35%), 121 (10%), 115 (10), 94 (10), 93 (100%), 92 (41%), 91 (20%), 77 (12%). 1H NMR (400 MHz, $CDCl_3$, 25 °C, TMS), δ = 1.28 (s, 3H; $C^{10}H_3$), 1.36 (s, 3H; C^9H_3), 1.45–1.55 (m, 1H; C^4H), 1.65–1.75 (m, 2H; C^3HH and C^5HH), 1.68 (s, 3H; C^7H_3), 2.05 (br.s., 1H; C^6H), 2.15–2.25 (m, 1H; C^5HH), 2.30–2.40 (m, 1H; C^3HH), 4.45 (br.d, 3J = 6.4 Hz, 1H; $C^{11}H$), 5.54 (br.s., 1H; C^2H), 6.15 (dd, 3J = 6.4 Hz, 3J = 16.1 Hz, 1H; $C^{12}H$), 6.55 (d, 3J = 16.1 Hz, 1H; $C^{13}H$), 7.17 (t, 3J = 7.3 Hz, 1H; $C^{17}H$), 7.26 (t, 3J = 7.3 Hz, 2H; $C^{16}H$ and $C^{18}H$), 7.35 ppm (br.s., 2H; $C^{15}H$ and $C^{19}H$). ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C, TMS), δ = 24.13 (C^9), 25.08 (C^7), 28.65 (C^{10}), 27.78 (C^3), 28.06 (C^5), 34.05 (C^4), 40.53 (C^6), 74.50 (C^{11}), 75.44 (C^8), 123.84 (C^2), 126.38 (C^{15} and C^{19}), 127.19 (C^{17}), 128.46 (C^{16} and C^{18}), 128.95 (C^{13}), 131.27 (C^{12}), 133.26 (C^1), 137.29 ppm (C^{14}). Minor isomer (longer GC retention time): MS (70 eV, EI): m/z 268 (0.1) [M^+], 136 (35%), 133 (41%), 121 (11%), 115 (9%), 94 (13%), 93 (100%), 92 (12%), 91 (21%), 80 (11%), 79 (11%), 77 (14%). For atom numbering see Scheme 2.

Compound 13: MS (70 eV, EI): m/z 206 (0.5) [M^+], 136 (50%), 121 (18%), 93 (100%), 92 (40%), 91 (20%), 77 (15%). For NMR data see [30].

Compound 14: MS (70 eV, EI): m/z 242 (0.5) [M^+], 136 (60%), 121 (12%), 93 (100%), 92 (50%), 91 (20%), 77 (11%). For NMR data see [31].



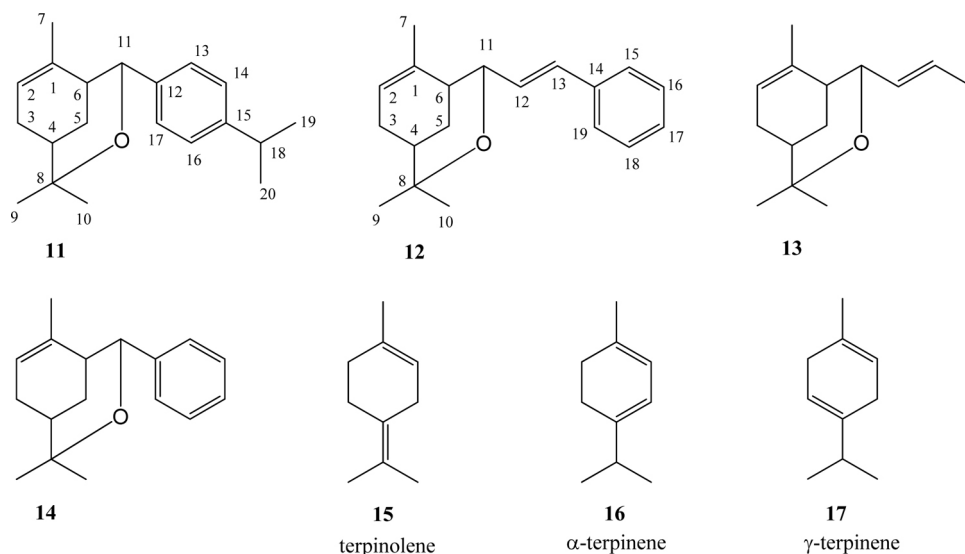
Scheme 1. Cycloaddition of limonene (1), α -terpineol (2), α -pinene (3), β -pinene (4), linalool (5) and nerol (6) to cuminaldehyde (7) in the presence of HPW/SiO₂ or CsPW.

3. Results and discussion

3.1. Reactions of terpenes with cuminaldehyde

Cuminaldehyde (7) is a naturally occurring monoterpene compound found in various essential oils such as of eucalyptus and myrrh oils. Due to the persistent pleasant smell cuminaldehyde is commercially used in perfumes and other cosmetics [1]. The addition of cuminaldehyde to other monoterpenes could result in oxygenated diterpenic compounds with interesting fragrance properties and/or biological activity.

Representative data on the reaction between cuminaldehyde (7) and limonene (1) in the presence of HPW/SiO₂ and CsPW catalysts in various solvents are collected in Table 1. In blank experiments with no catalyst added, limonene was virtually stable under the



Scheme 2. Products of cycloaddition of cuminaldehyde (11), *trans*-cinnamaldehyde (12), crotonaldehyde (13) and benzaldehyde (14) to monoterpenes and minor reaction products: terpinolene (15), α -terpinene (16) and γ -terpinene (17).

Table 1
Cycloaddition of cuminaldehyde (**7**) to limonene (**1**)^a.

Run	Catalyst (mg)	HPW or CsPW (μmol)	T (°C)	Time (h)	Conversion (%)	Selectivity (%) for		TON ^b
						11	(15 + 16 + 17) ^a	
1	Solvent: 1,2-dichloroethane HPW/SiO ₂ (10)	0.70	40	1	37	29	41	1000
				8	70	60	16	
2	HPW/SiO ₂ (15)	1.05	40	1	43	84	11	760
				8	80	82	10	
3	HPW/SiO ₂ (15)	1.05	50	1	62	78	15	935
				5	98	82	11	
4	HPW/SiO ₂ (20)	1.40	50	1	75	80	13	695
				5	97	82	11	
5 ^c	HPW/SiO ₂ (20)	1.40	50	1	63	80	14	1020
				5	95	80	13	
6 ^c	Solvent: diethylcarbonate (DEC) HPW/SiO ₂ (20)	1.40	60	1	57	80	17	975
				8	91	82	16	
7	CsPW (30)	9.00	60	1	30	84	13	80
				9	70	85	12	
8 ^d	CsPW (30)	9.00	60	1	48	82	12	110
				3	100	85	13	
9	CsPW (30)	9.00	70	1	97	80	16	100
				2	100	80	15	
10	Solvent: dimethylcarbonate (DMC) CsPW (30)	9.00	70	1	97	73	21	110
				2	100	80	16	
11	Solvent: 2-methyltetrahydrofuran (MeTHF) CsPW (30)	9.00	70	2	70	55	40	110
				7	99	81	10	

^a Limonene, 1.00 mmol; cuminaldehyde, 3.00 mmol; total volume, 3.0 mL. Conversion and selectivity (based on limonene) were obtained by GC. *Para*-menthenic monoterpenes: terpinolene (**15**), α -terpinene (**16**) and γ -terpinene (**17**) were formed in most of the runs in ca. 2:2:1 ratio.

^b TON (turnover number) was calculated as the moles of limonene reacted per mole of HPW or CsPW.

^c Limonene, 1.50 mmol.

^d Limonene, 0.45 mmol; cuminaldehyde, 2.25 mmol.

conditions used. The major reaction product was compound **11**; it was identified by MS and NMR as diterpenic ether shown in Schemes 1 and 2. The structure of **11** suggests that it results from the cyclization coupling of cuminaldehyde and limonene in which course the carbonyl carbon atom of the aldehyde bounds to the endocyclic allylic position of limonene and the oxygen atom to the central atom of the limonene isopropyl fragment. The selectivity for **11** was strongly affected by the reaction time and other reaction variables. Along with **11**, isomeric *para*-menthenic terpenes were formed from limonene under acidic conditions (mainly terpinolene (**15**), α -terpinene (**16**) and γ -terpinene (**17**), Scheme 2). Isolated ether **11** is a new compound, as far as we know, with a pleasant woody smell.

In 1,2-dichloroethane solutions in the presence of HPW/SiO₂ (0.1 wt% of the solid catalyst per the whole reaction mixture), 37% of limonene was converted in 1 h at 40 °C; however, the selectivity for **11** was only 29%, with other isomers of limonene being responsible for the rest of mass balance (Table 1, run 1). Further optimization of substrate concentration, catalyst loading and reaction temperature allowed us to achieve 80% selectivity for the desired ether **11** at nearly complete limonene conversion (Table 1, run 5). High turnover numbers obtained (up to 1000 per mole of HPW) illustrate high catalyst stability under the reaction conditions. Cuminaldehyde was used in a 3-fold excess in order to capture the limonene molecule thus disfavoring other acid-catalyzed transformations such as isomerization and oligomerization. Non-reacted aldehyde can be recovered and used in subsequent reaction cycles.

Important goal of the present work is to find viable eco-friendly alternatives for chlorinated solvents, which have been the solvents of choice for the reactions between aldehydes and terpenes in all previous reports [30–35]. After our previous failed attempts

to replace 1,2-dichloroethane in the reaction of benzaldehyde with terpenes by various conventional less hazardous solvents [31], we were very pleased to discover that limonene readily reacted with cuminaldehyde in diethylcarbonate (DEC) in the presence of HPW/SiO₂ catalyst, giving the same major product as in 1,2-dichloroethane. The reaction occurred with almost the same selectivity, albeit slower, probably due to stronger association of ionic pairs in less polar DEC (Table 1, cf. runs 6 and 5). The CsPW catalyst, also performed very well in the reaction of cuminaldehyde with limonene showing 85% selectivity for **11** at complete limonene conversions in DEC (Table 1, run 7–9) and 80% in DMC (Table 1, run 10).

Although HPW and CsPW are insoluble in low polar DEC and DMC (as well as in 1,2-dichloroethane), the stability of both towards leaching under reaction conditions was carefully verified by special experiments. After runs 6 and 7 (Table 1), the reaction mixtures were centrifuged for 20 min (20 °C, 18 000 rpm) in order to separate the catalyst. Tungsten content in the supernatants was determined by atomic absorption spectroscopy. In addition, to control HPW and CsPW leaching the activities of the supernatants were checked by allowing the reactions to proceed after adding new limonene portions. The supernatant after the run with CsPW (Table 1, run 7) showed no additional conversion and the tungsten content corresponded to less than 1.5% loss of CsPW. On the other hand, the supernatant after the run with HPW/SiO₂ (Table 1, run 6) contained 18% of tungsten originally used for the reaction; moreover, the supernatant was catalytically active converting 20% of the freshly added limonene in 5 h. Given the low solubility of HPW in non-polar solvents, we suspected that the problem was the separation of HPW/SiO₂ from the reaction mixture rather than HPW leaching. Indeed, a longer centrifugation (1.5 h) allowed for better removal

Table 2
Cycloaddition of cuminaldehyde (**7**) to α -terpineol (**2**)^a.

Run	Catalyst (mg)	HPW or CsPW (μmol)	T (°C)	Time (h)	Conversion (%)	Selectivity (%) for		TON ^b
						11	(1 + 15 + 16 + 17)^a	
Solvent: 1,2-dichloroethane								
1 ^c	HPW/SiO ₂ (15)	1.05	40	1	71	91	7	386
				2	90	90	8	
2 ^c	HPW/SiO ₂ (15)	1.05	50	1	96	82	11	428
				2	100	82	12	
3 ^c	HPW/SiO ₂ (15)	1.05	60	0.5	98	77	12	428
				2	100	76	12	
4 ^c	CsPW (30)	9.00	60	1	99	72	23	50
				5	100	72	20	
Solvent: diethylcarbonate (DEC)								
5 ^c	CsPW (30)	9.00	60	1	98	62	27	50
6 ^c	CsPW (30)	9.00	50	1	96	70	22	50
7 ^c	CsPW (30)	9.00	50	3	98	75	20	110
8 ^d	CsPW (10)	3.00	50	1	40	89	6	300
				12	90	93	5	
9	CsPW (10)	3.00	60	1	69	88	11	330
				5	98	87	10	
Solvent: dimethylcarbonate (DMC)								
10	CsPW (10)	3.00	60	1	66	77	15	330
				5	97	85	10	
Solvent: 2-methyltetrahydrofuran (MeTHF)								
11	CsPW (10)	3.00	60	5	20	96	3	66
12	CsPW (10)	3.00	70	1	20	90	4	330
				5	98	90	5	

^a α -Terpineol, 1.00 mmol; cuminaldehyde, 3.00 mmol; total volume, 3.0 mL. Conversion and selectivity (based on α -terpineol) were obtained by GC. *Para*-menthenic monoterpenes: limonene (**1**), terpinolene (**15**), α -terpinene (**16**) and γ -terpinene (**17**) were formed in most of the runs in ca. 2:2:2:1 ratio.

^b TON (turnover number) was calculated as the moles of α -terpineol reacted per mole of HPW or CsPW.

^c α -Terpineol, 0.45 mmol; cuminaldehyde, 2.25 mmol.

^d After the reaction, the catalyst was centrifuged from the reaction mixture, washed with chloroform and reused two times without a significant decrease in activity and selectivity.

of HPW/SiO₂ and the supernatant was no longer active in the limonene conversion. Although both HPW/SiO₂ and CsPW catalysts performed truly heterogeneously, taking into account the easier CsPW separation, further work in DEC/DMC solutions was carried out with the CsPW catalyst.

The reaction of cuminaldehyde with α -terpineol (**2**), another *para*-menthenic terpene, in the presence of HPW/SiO₂ or CsPW catalysts mainly gave the same ether **11** (Table 2). High selectivity of 90% at a nearly complete α -terpineol conversion was observed in 1,2-dichloroethane solutions at 40 $^{\circ}$ C, whereas at 50 and 60 $^{\circ}$ C the selectivity was slightly lower (ca. 80%) (Table 2, run 1 vs. runs 2 and 3). Limonene and other *para*-menthenes (α -terpinene, γ -terpinene and terpinolene) were detected as minor by-products. Unfortunately, the amount of *para*-menthenes did not significantly decrease at longer reaction times, when the reaction mixture was left in contact with the catalyst after complete conversion of α -terpineol (Table 2, runs 2 and 3). The reaction also readily occurred in the presence of CsPW catalyst (Table 2, run 4).

DEC and DMC also proved to be excellent alternatives for 1,2-dichloroethane to perform the reaction of cuminaldehyde with α -terpineol (Table 2, runs 5–10). After optimization of reaction variables, complete conversions of α -terpineol were obtained for reasonably short reaction times with 85–87% selectivity for the desired product **11** and high TONs (Table 2, runs 9 and 10). Noteworthy, the reactivity of α -terpineol was much higher than that of limonene; under similar reaction conditions, 98% of α -terpineol was consumed within 1 h, compared to only 48% of limonene (run 5 in Table 2 vs. in run 8 in Table 1). On the other hand, the reaction with limonene was more selective to the desired ether **11** than the reaction with α -terpineol. The CsPW catalyst could be easily separated by centrifugation and reused. In run 8 (Table 2), the catalyst

was reused two times after washing with chloroform without any significant decrease in activity and selectivity.

The reaction can also be carried out in 2-methyltetrahydrofuran (MeTHF), which is considered a biomass-based alternative to chlorinated solvents [46,47]. MeTHF is produced from furfural or levulinic acid, which are renewable precursors available from lignocellulosic biomass. Among other properties of MeTHF are its abiotic degradability, low toxicity and better stability compared to other ether solvents. On the other hand, it should be mentioned that MeTHF is considered a less green solvent than DEC and DMC, in particular, due to the low life cycle assessment score [48]. MeTHF and 1,2-dichloroethane have similar polarity (ϵ = 10.4 and 7.0, respectively); however, MeTHF possesses higher Lewis basicity, which could decrease the acid strength of acid catalysts. As expected, the reaction of cuminaldehyde with α -terpineol occurred slower in MeTHF than in DEC and DMC, nevertheless it had excellent 96% selectivity for product **11** (Table 2, run 11 vs runs 9 and 10). At a higher temperature of 70 $^{\circ}$ C, the reaction in MeTHF could be run faster to be completed within 5 h with 90% selectivity for ether **11** and high TONs (Table 2, run 12). Encouraged by this result, we tested the reaction with less reactive limonene in MeTHF solutions and also observed efficient catalytic performance of CsPW (Table 1, run 11). These two reactions represent examples of truly green synthetic processes which occur with 100% atom efficiency under mild conditions and use only biomass-derived renewable organic materials – both the reagents and the solvent.

α -Pinene (**3**), one of the more widespread terpenic compounds available from turpentine oils obtained from coniferous trees, also gives ether **11** with good selectivity reacting with cuminaldehyde in the presence of HPW/SiO₂ or CsPW (Table 3). The reaction readily occurred in 1,2-dichloroethane with high TONs and 80% selectivity for **11** at a complete substrate conversion (Table 3, run 1). 1,2-

Table 3
Cycloaddition of cuminaldehyde (7) to α -pinene (3)^a.

Run	Catalyst (mg)	HPW or CsPW (μ mol)	T ($^{\circ}$ C)	Time (h)	Conversion (%)	Selectivity (%) for		TON ^b
						11	(1 + 15 + 16 + 17) ^a	
1	Solvent: 1,2-dichloroethane HPW/SiO ₂ (15)	1.05	50	0.25	100	80	14	952
				2	100	80	8	
2	Solvent: diethylcarbonate (DEC) HPW/SiO ₂ (15)	1.05	50	0.25	91	68	26	952
				2	100	75	22	
3	HPW/SiO ₂ (15)	1.05	60	0.25	99	67	27	952
				2	100	72	21	
4	CsPW (15)	4.50	60	0.25	99	51	33	220
				2	100	68	21	
5	CsPW (15)	4.50	50	2	99	61	25	300
6	CsPW (10)	3.00	50	2	89	54	27	222
7	CsPW (30)	9.00	40	5	100	68	24	111

^a α -Pinene, 1.00 mmol; cuminaldehyde, 3.00 mmol; total volume, 3.0 mL. Conversion and selectivity (based on α -pinene) were obtained by GC. *Para*-menthenic monoterpenes: limonene (1), terpinolene (15), α -terpinene (16) and γ -terpinene (17) were formed in most of the runs in ca. 2:2:2:1 ratio.

^b TON (turnover number) was calculated as the moles of α -pinene reacted per mole of HPW or CsPW.

Table 4
Cycloaddition of cuminaldehyde (7) to β -pinene (4)^a.

Run	Catalyst (mg)	HPW or CsPW (μ mol)	T ($^{\circ}$ C)	Time (h)	Conversion (%)	Selectivity (%) for		TON ^b
						11	(1 + 15 + 16 + 17) ^a	
1	Solvent: 1,2-dichloroethane HPW/SiO ₂ (15)	1.05	50	0.25	100	66	12	950
				0.25	100	65	14	
2	HPW/SiO ₂ (10)	0.70	50	0.25	100	65	14	1430
				0.25	100	56	16	
3	HPW/SiO ₂ (10)	0.70	25	0.25	100	56	16	1430
				0.5	100	54	15	
4	CsPW (30)	9.00	50	0.5	100	54	15	110
				0.5	100	54	15	
5	Solvent: dimethylcarbonate (DMC) CsPW (30)	9.00	50	0.5	100	45	13	110
				0.5	96	30	15	
6	CsPW (10)	3.00	50	0.5	96	30	15	320

^a β -Pinene, 1.00 mmol; cuminaldehyde, 3.00 mmol; total volume, 3.0 mL. Conversion and selectivity (based on β -pinene) were obtained by GC. *Para*-menthenic monoterpenes: limonene (1), terpinolene (15), α -terpinene (16) and γ -terpinene (17) were formed in most of the runs in ca. 2:2:2:1 ratio; oligomerization products (not detectable by GC) accounted for the rest of the mass balance.

^b TON (turnover number) was calculated as the moles of β -pinene reacted per mole of HPW or CsPW.

Dichloroethane can be replaced by DEC (Table 3, runs 2 and 3). The CsPW catalyst is preferred due to its easier separation from DEC solutions as compared to HPW/SiO₂ (Table 2, runs 4–7). It is important that in most cases the selectivity increased with reaction time due to transformation of isomeric monoterpenes rapidly formed at early reaction stages to ether 11.

The same product 11 was obtained in the reaction between cuminaldehyde and β -pinene (4) in 1,2-dichloroethane (up to 66% yield) and in DMC (45% yield) (Table 4). β -Pinene reacted under acidic conditions very rapidly even at room temperature (Table 4, run 3), giving 11 and isomeric monoterpenes together with non-detectable (GC) high-boiling by-products. Differently from the examples described above, the selectivity for ether 11 in the reaction with β -pinene did not increase with the reaction time. Two monoterpenic allylic alcohols, linalool (5) and nerol (6), were also coupled with cuminaldehyde in the presence of CsPW catalyst in DEC solutions to give 11 as the major product. After optimization, ether 11 was obtained from nerol in 62% yield, whereas from linalool only in 34% yield due to formation of significant amounts of isomeric *para*-menthenes and high-boiling oligomers (Table 5, runs 1 and 2, respectively).

3.2. Reactions of terpenes with other aldehydes in diethylcarbonate solutions

Representative results for the reactions of limonene and α -terpineol with *trans*-cinnamaldehyde (8), crotonaldehyde (9) and benzaldehyde (10) in DEC solutions are collected in Table 5 (runs 3–8). After optimization, these reactions gave the corresponding oxabicyclo[3.3.1]nonene compounds in good to excellent yields (all had pleasant fragrance characteristics after isolation).

Cinnamaldehyde is a natural product occurring in high concentrations in cinnamon essential oils, predominately as *trans* (E) isomer. Due to its pleasant smell and low toxicity this compound has found numerous commercial applications as a flavoring agent in food and perfume industries and is also used as a fungicide and insecticide agent in agriculture. Cycloaddition of *trans*-cinnamaldehyde to limonene and α -terpineol resulted in the same product, oxabicyclic compound 12 (Table 5, runs 3 and 4; for the structure of 12 see Scheme 2). As far as we know, this is a new compound; two stereoisomers of 12 with virtually the same mass spectra were detected in the reaction solutions, in most cases in the ratio of ca. 9/1.

Table 5
CsPW catalyzed cycloaddition of aldehydes to monoterpenes in diethylcarbonate solutions^a.

Run	Substrate	Aldehyde	CsPW (μmol)	T ($^{\circ}\text{C}$)	Time (h)	Conversion (%)	Product (selectivity, %)	Selectivity (%) for (1 + 15 + 16 + 17) ^a	TON ^b
1	Linalool (5)	Cuminaldehyde (7)	9	50	3	100	11 (34)	16	110
2	Nerol (6)	Cuminaldehyde (7)	9	60	3	100	11 (62)	19	110
3 ^c	Limonene (1)	Cinnamaldehyde (8)	9	50	9	90	12 (90)	7	45
4	α -Terpineol (2)	Cinnamaldehyde (8)	3	70	5	95	12 (85)	12	320
5 ^d	Limonene (1)	Crotonaldehyde (9)	9	80	8	90	13 (81)	8	100
6 ^e	α -Terpineol (2)	Crotonaldehyde (9)	3	60	7	90	13 (80)	6	300
7 ^f	Limonene (1)	Benzaldehyde (10)	3	60	12	92	14 (86)	9	300
8 ^g	α -Terpineol (2)	Benzaldehyde (10)	3	60	6	98	14 (91)	7	330

^a Substrate, 1.00 mmol; aldehyde, 3.00 mmol; CsPW, 10 or 30 mg (3 or 9 μmol); total volume, 3.0 mL. Conversion and selectivity (based on the reacted substrate) were obtained by GC. *Para*-menthenic monoterpenes: limonene (**1**), terpinolene (**15**), α -terpinene (**16**) and γ -terpinene (**17**) were formed in most of the runs in ca. 2:2:2:1 ratio.

^b TON (turnover number) was calculated as the moles of the substrate reacted per mole of CsPW.

^c Substrate, 0.45 mmol; aldehyde, 2.25 mmol.

^d 70% isolated yield of **13**.

^e 68% isolated yield of **13**.

^f 70% isolated yield of **14**.

^g 80% isolated yield of **14**.

Cycloaddition of crotonaldehyde (**9**) and benzaldehyde (**10**) to either limonene or α -terpineol in DEC gave analogous products **13** and **14** (Scheme 2), respectively, with 80–90% selectivity at nearly complete substrate conversions (Table 5, runs 5–8). These results represent additional evidence for the viability of organic carbonates as green solvents in the reactions of terpenic compounds with aldehydes to replace toxic chlorinated solvents – the only class of solvents which has shown satisfactory performance in all previous studies. To verify the reagent scope, the aldehyde in the reaction with α -terpineol was substituted by methyl ketones: methyl ethyl ketone or β -ionone [4-(2,6,6-trimethyl-1-cyclohexenyl)-3-buten-2-one] under the conditions of runs 6 and 8 in Table 5. In both runs, no products of possible coupling of α -terpineol with ketones were detected.

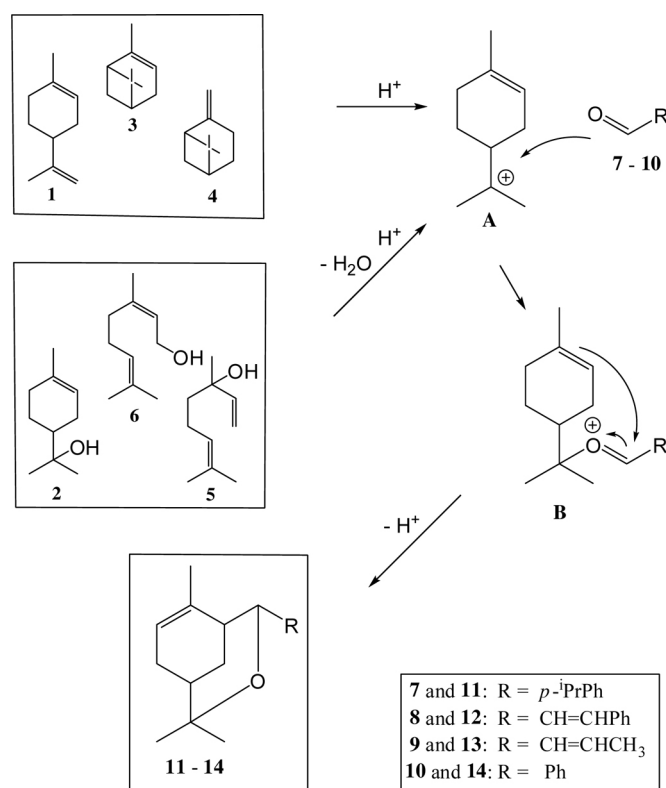
3.3. Proposed mechanism

A plausible mechanism for the cycloaddition of aldehydes to monoterpenic compounds is shown in Scheme 3. Given that all monoterpenes form the same type of product (**11**–**14**) regardless of the aldehyde used, it is conceivable that α -terpenyl carbenium ion **A** is a common intermediate in all these cycloadditions. Protonation of limonene and protonation/dehydration of α -terpineol give the carbocation **A** directly. Other substrates, such as α -pinene, β -pinene, linalool and nerol, first give different carbenium ions under acidic conditions (their structures are not shown in Scheme 3); these can isomerize rapidly into carbocation **A**, which seems to be more stable under the reaction conditions. Interaction of the aldehyde with carbenium ion **A** results in the formation of oxocarbenium intermediate **B**. Subsequent oxonium-ene cyclization via intramolecular attack of the carbon-carbon double bond on the oxocarbenium ion results in oxabicyclic products **11**–**14**.

In principle, carbenium ion **A** can lose a proton before interacting with aldehyde to give other *para*-menthenic terpenes such as terpinolene, α -terpinene and γ -terpinene, detected as main by-products in our systems. Interaction of the ionic intermediates with the monoterpene substrates can also lead to high molecular weight by-products (herein referred to as oligomers). To minimize these undesirable transformations and improve the selectivity for ethers **11**–**14**, a large (3-fold) excess of aldehydes was used in our reaction protocols, which allowed efficient trapping of intermediate **A**.

4. Conclusions

The acidic Cs salt of tungstophosphoric heteropoly acid, $\text{Cs}_{2.5}\text{H}_{0.5}\text{PW}_{12}\text{O}_{40}$, is excellent solid acid catalyst for liquid-phase



Scheme 3. Proposed mechanism of cycloaddition of limonene (**1**), α -terpineol (**2**), α -pinene (**3**), β -pinene (**4**), linalool (**5**) and nerol (**6**) to cuminaldehyde (**7**), *trans*-cinnamaldehyde (**8**), crotonaldehyde (**9**) and benzaldehyde (**10**).

cycloaddition reactions between naturally occurring monoterpenes and aldehydes, including also biomass-derived aldehydes. The reactions result in theoxabicyclo[3.3.1]nonene compounds, which are difficult to obtain by conventional synthetic methods. These compounds are potentially useful for the fragrance and pharmaceutical industries. The catalyst does not suffer from leaching and can be easily separated from the reaction media. Relatively low boiling points of the solvents used allow for their easy removal by distillation. It has been shown in special experiments that all the products are stable at the temperature required for the solvent distillation. High atom economy, mild reaction conditions, low catalyst loadings and the use of non-toxic biodegradable “green” organic solvents, such as dimethylcarbonate, and diethylcarbonate, are important advantages of the developed environmentally

benign catalytic protocol for upgrading bio-renewable materials into value-added products.

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